CONF-8510173--30

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MASTER

NOV 26 1985

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CONF-8510173--30

TI86 003304

For Publication in the Proceedings of the 13th Water Reactor Safety Research Information Meeting at the National Bureau of Standards, Gaithersburg, Maryland, October 22—25, 1985.

*Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under Interagency Agreement 40-551-75 and 40-552-75 with the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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ABSTRACT

The behavior of aerosols assumed to be characteristic of those generated during light water reactor (LWR) accident sequences and released into containment is being studied. Recent activities in the ORNL Aerosol Release and Transport Project include studies of (1) the thermal hydraulic conditions existing during Nuclear Safety Pilot Plant (NSPP) aerosol tests in steam-air environments, (2) the thermal output and aerosol mass generation rates for plasma torch aerosol generators, and (3) the influence of humidity on the shape of agglomerated aerosols of various materials. A new Aerosol-Moisture Interaction Test (AMIT) facility was prepared at the NSPP site to accommodate the aerosol shape studies; several tests with Fe_2O_3 aerosol have been conducted. In addition to the above activities a special study was conducted to determine the suitability of the technique of aerosol production by plasma torch under the operating conditions of future tests of the LWR Aerosol Containment Experiments (LACE) at the Hanford Engineering Development Laboratory.

INTRODUCTION

The behavior of aerosols assumed to be characteristic of those generated during light water reactor (LWR) accident sequences and released into containment is being studied in the Nuclear Safety Pilot Plant (NSPP) which is located at the Oak Ridge National Laboratory (ORNL). This project is sponsored by the Division of Accident Evaluation, Nuclear Regulatory Commission, and the purpose is to provide experimental data for qualification of LWR aerosol behavior codes under development.

During the past year, several significant changes in the scope of this project have occurred. During a joint NRC aerosol modelers/experimenters meeting in 1984,[1] several areas were identified in which additional experimental information was needed. New activities to develop this information include the study of (1) the thermal hydraulic conditions existing during NSPP aerosol tests in steam-air environments, (2) the thermal output and aerosol mass generation rates for plasma torch aerosol generators, and (3) the influence of humidity on the shape of agglomerated aerosols of various materials. To accommodate this change in scope and to accelerate the development of this needed information, future multicomponent aerosol tests in the NSPP will be conducted at a much lower frequency.

A new facility was prepared at the NSPP site to accommodate the study of the effect of various levels of humidity on the physical characteristics (shape factors) of aerosols of interest in LWR accident sequences. The test vessel (0.56 m^3) features a humidity measurement and control system as well as provisions for the measurement of aerosol number concentration, mass concentration, and particle size distribution, and for the acquisition of aerosol samples for electron microscopy. The Aerosol-Moisture Interaction Test (AMIT) facility is now operational and two tests with Fe_2O_3 aerosol have been conducted.

As part of the NRC support of the LACE Program at Hanford, a special study was conducted to determine the suitability of the technique of aerosol production by plasma torch aerosol generators under the operating conditions of future LACE tests. Demonstrations of the production of manganese (Mn) aerosol at elevated temperatures and pressure were carried out. The final test was a study of the behavior of manganese oxide (Mn_2O_3) aerosol in the NSPP vessel in a steam-air environment.

EXPERIMENTAL

1. Thermal Hydraulic Conditions During NSPP Aerosol Tests

It is apparent from the results of prior aerosol-steam tests in the NSPP that the thermal hydraulic conditions within the vessel have a strong influence on the behavior of the aerosol. The decision was made to (1) upgrade the quality of the input steam and the device for the measurement of steam mass input, (2) refine the measurements of thermal hydraulic parameters during some additional "steam-only" tests, and (3) apply the results from these new steam tests to effect a better definition of the degree of water vapor saturation in prior NSPP steam-aerosol tests. Data from the "steam-only" tests also provide a small data base for comparison with thermal hydraulic output from the CONTAIN code.

The steam supply system to the NSPP vessel now contains a steam separator, a steam superheater and a vortex flowmeter; accurate measurements are made of the temperature and pressure of the steam flow to the vessel. In addition the insulation on the NSPP vessel has been upgraded.

Of the large number of aerosol-steam tests that have been run, attention will be limited to those for which vortex flowmeter data are available, because these tests enable checks on steam behavior to be carried out with greater confidence. In addition, several "steam-only" tests were run to check the calibration of the vortex flowmeter and to observe the behavior of steam within the vessel. The tests involved are listed in Table 1. The prior aerosol-steam tests were all run under the "old insulation" conditions. The vessel was not insulated on the top flange or on a flange near the bottom; the stiffening ribs around the vessel circumference were only partially insulated. In the "new insulation" condition the flanges and ribs were insulated and the remaining insulation was sealed to curb air leaks.

1.1 Steam Flow Rates

Steam flow rates are measured with the vortex flowmeter and the measurement is accurate as long as the steam quality is not less than 1. The steam flow rate can also be estimated from weights of steam condensate collected at various times during a test. Customarily, the condenate in the vessel is drained into a weigh tank when the temperature and

Table 1. Aerosol-Steam and Steam-Only Tests in the Nuclear Safety Pilot Plant (NSPP)

Test	Aerosol	Insulation condition	Steam superheater used
53	None	Old	Yes
54	None	Old	Yes
55	None	New	Yes
56	None	New	Yes
407	U_3O_8	Old	No
522	Concrete	Old	No
612	Fe_2O_3 + U_3O_8	Old	No
613	Fe_2O_3 + U_3O_8	Old	No

pressure within the vessel have reached a steady state and just before aerosol generation is started. The vessel is drained again at the conclusion of the test when the vessel has cooled. The vortex flowmeter data for steam flow rate were integrated over the time of steam injection and the resulting estimates of total steam condensate are compared

Table 2. Comparison of Steam Condensate Collected and that Amount Estimated from Vortex Flowmeter Measurements

Test	Steam condensate (kg)		Measured steady state flowrate (g/s)
	Collected	Estimated	
Steam-only			
53	227	206	-
54	257	246	-
55	213	207	-
56	217	222	-
Aerosol-steam			
407	385	336	7.0
522	363	291	5.5
612	359	334	8.2
613	368	299	6.3

with measured condensate in Table 2. The results for the "steam-only" tests 53-56 show better agreement with the amount of condensate collected and the amount of condensate estimated from vortex flowmeter data than do the results from the prior aerosol tests in steam-air environments. This disparity strongly suggests that in all the aerosol tests the steam supply contained liquid water. The vortex flowmeter measurements, which are based on gas phase flow, were insensitive to the mass of liquid phase introduced.

For standard NSPP aerosol tests in steam the steam flow rates are about 35 g/s during heatup of the vessel and are about 7 g/s at the steady state conditions under which the test aerosol is introduced.

1.2 Steam Saturation Conditions

The test environment in the NSPP vessel is a mixture of steam, air and gases added by plasma torch operation. Because of the observed influence of steam on both the shape and the aerodynamic behavior of test aerosols, it is of interest to better define the degree of steam saturation that exists in the NSPP vessel during aerosol tests. Refined measurements of thermal hydraulic conditions during the "steam-only" tests provided the data and insight to allow a reevaluation of conditions during prior aerosol-steam tests.

To prepare the test environment the vessel is evacuated to a low pressure, typically -62 to -69 kPa gauge pressure (-9 to -10 psig).

Steam is then introduced at high mass flow rates to heat the vessel and its contents and achieve the preselected test temperature and resultant pressure. At this point the steam flow rate is reduced to maintain steady-state conditions. The accumulated steam condensate is removed from the vessel just prior to start of aerosol generation by the plasma torch aerosol generator.

Argon and some hydrogen and oxygen gases are introduced by operation of the plasma torch. Table 3 lists the pretest air pressure and temperature together with calculated values of the air and torch gas partial pressures at test conditions for selected NSPP tests. The initial air pressure listed is the gauge pressure corrected by the barometric pressure and also corrected for an assumed saturated water vapor level. The experimental temperatures cited are the time-averaged values from 12 thermocouples distributed at three elevations within the vessel. The pressure contribution from the torch gas was computed on the basis of torch gas volume estimates from NSPP Run 522; this estimate was adjusted for each case by the length of time of plasma torch generator operation.

Table 3. Partial pressures of air and other gases in various NSPP tests

Experiment	Pre-test conditions		Test conditions		
	Initial air pressure (MPa)	Presteam temperature (K)	Experiment temperature (K) (MPa)	Partial pressure of air in experiment (MPa)	Partial pressure other gases
53	0.02998	297	370	0.04521	
54	0.02549	300	384	0.03266	
55	0.02481	301	377	0.03111	
56	0.02652	299	386	0.03425	
407	0.03426	299	386	0.04426	0.00141
522	0.02538	298	379	0.03233	0.01087
612	0.03086	297	387	0.04022	0.01078
613	0.03190	297	384	0.04125	0.01017

In Table 4 the sum of the calculated partial pressures of air and torch gases (from Table 3) is compared with the time-averaged pressure difference between the measured vessel pressure and the pressure of saturated steam at the temperature of the test environment. The average value of the pressure differences is 0.0070 MPa; at 115°C, a 1° change in the temperature of the test environment will result in a pressure change of about 0.0056 MPa. Thus, the pressure difference could result from a temperature change of 1.3°C which is within the accuracy of the thermocouples used (±2°C). The pressure difference observed between the total system pressure and the pressure of saturated steam seems attributable entirely to the presence of air and torch gases.

Table 4. Partial pressure of air and torch gases compared with the difference between the measured vessel pressure and the saturation pressure of steam at the vessel temperature

Test	Calculated pressure of air and torch gases (MPa) (2)	(Vessel pressure) − (sat. steam press.) (MPa) (3)	(Column 2) − (Column 3) (MPa)
53	0.04521	0.04832	−0.00311
54	0.03266	0.03243	0.00023
55	0.03111	0.03475	−0.00364
56	0.03425	0.04197	−0.00772
407	0.04567	0.05775	−0.01208
522	0.04320	0.05494	−0.01174
612	0.05100	0.06076	−0.00976
613	0.05142	0.05988	−0.00846

It is concluded, based upon the results of these exercises, and upon observed steam conditions within the vessel, that the atmosphere in the vessel during aerosol-steam tests was saturated within the ability of the measurement techniques to detect it.

2. Thermal Output and Aerosol Generation Rates for Plasma Torch Aerosol Generators

A small (0.35-m^3) test vessel was prepared for a series of development tests to obtain detailed information on the operating characteristics of the plasma torch aerosol generator (e.g., thermal output and aerosol mass generation rates) used for the generation of Fe_2O_3 and concrete aerosols in NSPP tests. A rack containing 24 thermocouples (6 at each of 4 axial locations) was assembled for measurement of gas temperatures inside the test vessel. These thermocouples, along with outside-wall thermocouples and heat flux meters, are used to monitor the thermal input to the vessel by the aerosol generator, which is installed at one end of the cylindrical vessel. In addition, plasma torch power level and heat loss to cooling water flows are measured.

Two development tests have been conducted (NSPP-DT-1 and NSPP-DT-2) each of which consisted of several subtests; the key parameter for two subtests of NSPP-DT-2 are listed in Table 5.

Table 5. Parameters for plasma torch generator tests

Run	Torch power (kW)	Duration of operation (s)	Iron powder feed (g)	Vessel pressure (MPa)
NSPP-DT-2-2	37	120	0	0.2
NSPP-DT-2-3	44	120	93	0.17

2.1 Thermal Output (Heat Input to Vessel)

Assessment of heat input to the vessel (or thermal output from the torch) is considerably more complicated than the measurement of aerosol mass output. The steps taken in heat input analysis will be outlined below.

A control volume approach was used for heat input analysis, as shown in Fig. 1. With reference to the control volume, the energy should be conserved at any instant as given by

$$\dot{H} + \dot{R} = \dot{I} + \dot{S} + \dot{L} , \qquad (1)$$

where $\dot{H}$, $\dot{R}$, $\dot{I}$, $\dot{S}$, and $\dot{L}$ indicate, respectively, the rates of change of enthalpy influx, of heat transfer by radiation from the torch, of internal energy, of stored energy in the vessel wall, and of heat loss. The instantaneous energy balance as represented in Eq. (1) could not be used in this form because of lack of radiation measurements.

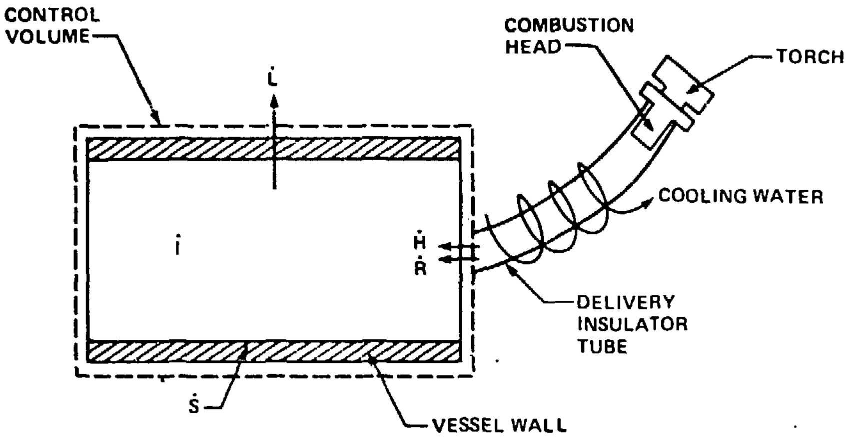

Fig. 1. Heat flow diagram of test vessel with plasma torch assembly.

A more practical approach is the so-called integrated energy balance that represents the energy balance over the torch operating duration,

$$\int_0^{\tau} \dot{H}dt + \int_0^{\tau} \dot{R}dt = \int_0^{\tau} \dot{I}dt + \int_0^{\tau} \dot{S}dt + \int_0^{\tau} \dot{L}dt \ , \tag{2}$$

where τ signifies the torch operating time. In Eq. (2) each term can be calculated from the monitored data except radiation.

An even more useful consideration is the integrated energy balance over an infinite time span,

$$\int_0^{\infty} \dot{H}dt + \int_0^{\infty} \dot{R}dt = \int_0^{\infty} \dot{L}dt \ . \tag{3}$$

Equation (3) establishes the fact that the total heat input equals total heat loss provided the data record is much longer than the torch operating duration. This condition was met satisfactorily in both NSPP-DT-2-2 and NSPP-DT-2-3 tests. Therefore, a calculation of net heat input become a calculation of total heat loss, thus avoiding the unknown heat input by radiation. Calculations of heat loss were made possible by use of continuous heat flux meter data. Over a long record span, heat flux meters, in fact, work as calorimeters.

When the integration is extended from a finite time span [Eq. (2)] to an infinite time span [Eq. (3)], the internal energy and wall-stored energy terms vanish because the final state coincides with the initial state as time approaches infinity.

The estimates of heat input are presented in Table 6. It is shown that (1) for test DT-2-2, the heat input to the vessel is about 10% of the torch power and the amount of internal energy increase is ~10% of the heat input and (2) for DT-2-3 test, heat input to the vessel is also about 10% of the torch power but the amount of internal energy increase is only about 5% of the heat input.

Table 6. Results for heat input in tests NSPP-DT-2-2 and NSPP-DT-2-3

Test	Torch energy (kJ)	Heat removed by cooling water (kJ)	Heat input (kJ)	Increase of internal energy (kJ)
DT-2-2 without Fe_2O_3	4430	2520	410	37
DT-2-3 with Fe_2O_3	5270	3148	500	22

The finding that heat input is about 10% of the torch energy has been applied to NSPP steam test analysis based on the fact that the configuration of the plasma torch assembly remained unchanged. Some significant results for NSPP run 522 (Ref. 2) are summarized in Table 7. There, the first column is 10% of the electrical energy input to the plasma torch; the second column is the total enthalpy of the steam fed to the vessel over a 6-h period; the third column is the internal energy of the steam in the vessel just before the torch was started; the last column is the change in internal energy of the vessel atmosphere during torch operation based on the observed temperature rise during that period. These findings indicate that it is highly unlikely that plasma torch operation has had a major effect on the conditions of the NSPP vessel environment during previous aerosol-steam experiments. In run 522 the internal energy input by the plasma torch is small (~0.2%) compared with the internal energy of the steam at the quasi-steady-state conditions of the experiments.

2.2 Aerosol Generation

The Fe_2O_3 aerosol generation efficiency and generation rate were determined by posttest collection of all deposited material from within the test vessel, aerosol generator, and delivery tube. The collected terial was processed through a 100-mesh sieve to remove metal slag and large particles of metal; the material passing through the sieve was assumed to be Fe_2O_3 aerosol material. The aerosol-generation efficiency was calculated by comparing the mass of Fe metal powder (as Fe_2O_3) passed

Table 7. Heat input results — NSPP Run 522

Heat input (kJ)		In-vessel steam internal energy (kJ)	Torch-induced increase of internal energy (kJ)
Torch generated	Steady state steam		
8.53×10^3	3.21×10^5	6.66×10^4	1.35×10^2

through the generator with the mass of aerosol material collected from within the test system. For NSPP-DT-2-3, the Fe_2O_3 aerosol-generation efficiency was ~25%. The aerosol mass generation rate was calculated by dividing the mass of Fe_2O_3 aerosol material collected by the duration of aerosol-generator operation. For this test the value was ~0.28 g/s.

3. Influence of Humidity on Shape of Agglomerated Aerosols

A new project was initiated, and a facility prepared, to study the effect of various levels of humidity on the physical characteristics of aerosols of interest in LWR accident sequences. It has been observed in the NSPP test program[3] that agglomerated aerosols of U_3O_8 or Fe_2O_3 are chain-like in appearance under relatively dry conditions and as spheroidal clumps under humidities of ~100%. It is of interest to determine the humidity level at which this transition occurs.

3.1 AMIT Facility

The Aerosol-Moisture Interaction Test (AMIT) facility has been prepared for conduct of these tests. The test vessel (0.52 m^3) is insulated and has both heating and cooling coils for temperature control. Features of the system (Fig. 2) include a humidity measurement and control system; this external loop system consists of an optical condensation hygrometer for humidity determination, components for water vapor injection and/or removal, and flow measurement and control devices. Aerosol parameters measured are mass concentration, number concentration, size distribution, and shape by microscopy; system parameters measured are temperature, pressure, and relative humidity (RH). Aerosol generation is by plasma torch.

A series of development tests was conducted in the 0.35 m^3 test vessel (described in Sect. 2) to determine suitable plasma torch aerosol generator operating parameters for the generation of Fe_2O_3 aerosol to use in the AMIT tests. Heat and gas input into the AMIT vessel atmosphere during aerosol generation must be minimized to reduce perturbations in the humidity level specified for each test.

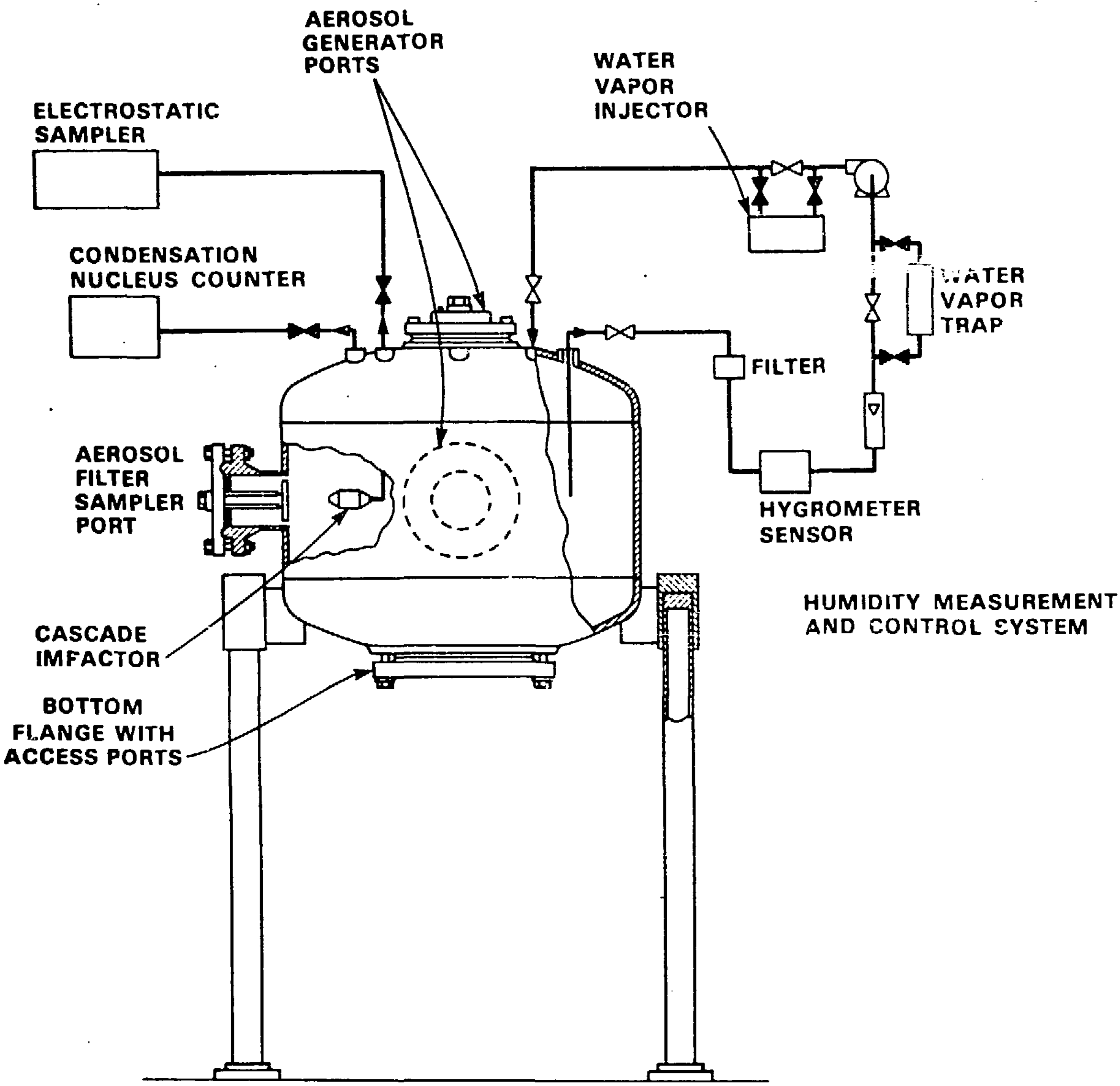

Fig. 2. Schematic of Aerosol-Moisture Interaction Test (AMIT) Facility.

3.2 AMIT Experiments

A preliminary test without aerosol generation was conducted to determine humidity level perturbations associated with plasma torch operation under the parameters selected for Fe_2O_3 aerosol generation. This test was conducted in two parts at initial relative humidity (RH) levels of 45 and 75%, respectively. There was a net increase in absolute humidity level associated with the plasma torch operation which was apparently due to the water vapor formed from the H_2 and O_2 components of the gas mixture used in the Fe_2O_3 aerosol generation. This increase was from 45 to 59% RH and from 75 to 84% RH in the two subtests, respectively. The new equilibrium humidity value was reached within ~10 minutes after termination of the 60-s torch operation period. There was an initial depression in the indicated RH as a result of a 6°C increase in test vessel gas temperature; the gas temperature quickly returned to a value equivalent to the vessel wall temperature, and the measured RH value rose to the value reported.

AMIT-5001 is the designation for the first of the planned aerosol tests; this test was conducted with Fe_2O_3 aerosol at 54% RH. The aerosol was produced with the plasma torch aerosol generator over a 30-s period and was injected into the test environment which was at 48% RH. The RH increased from the initial value of 48% to 54% as a result of torch operation. The increase was smaller than noted in the preliminary test and could have resulted from either a reduced production of water due to consumption of part of the available oxygen by oxidation of the iron vapor or loss of water vapor from the gas space by adsorption onto the surfaces of the aerosol.

During the 2-h period following aerosol generation, nine filter samples, two cascade impactor samples, and five electrostatic precipitator samples were taken for determination of aerosol mass concentration as a function of time, particle size distribution, and physical characteristics of the aerosol, respectively. The maximum aerosol concentration was ~2 g/m^3 based upon data obtained from the filter samples and the cascade impactor samples.

The aerodynamic mass medium diameter (AMMD) of the aerosol was measured using cascade impactors (Andersen Mark III). Two samples as a function of elapsed time were taken for size analysis: one was taken inside the vessel with the impactor under existing vessel conditions of temperature and pressure, and the other one was taken outside the vessel, again with the impactor under approximately the existing vessel conditions of temperature and pressure. The internal impactor indicated an AMMD of 3.7 μm at 18.2 min after start of aerosol generation while the external impactor indicated an AMMD of 2.4 μm at 44.4 min.

Results from scanning electron microscopy (SEM) analysis of the five electrostatic precipitator samples indicated that essentially all of the Fe_2O_3 was in the form of chain-like agglomerates.

The AMIT-5002 test was conducted with Fe_2O_3 aerosol at an initial RH of 73%, which increased to a final value of 79% after operation of the plasma torch. As in the first test (AMIT-5001), results from scanning electron microscopy (SEM) analysis of the five electrostatic precipitator samples indicated that essentially all of the Fe_2O_3 aerosol was in the form of chain-like agglomerates.

4. LACE Program Support Work

As part of the NRC support of the LACE Program at Hanford, a development effort was carried out to determine the suitability of plasma torch aerosol generators for the production of manganese aerosols under the operating conditions of future LACE tests. Several preliminary tests (LACE-DT-1 through LACE-DT-5) in the 0.35-m^3 vessel without aerosol generation were first completed to determine the torch operating parameters necessary for operation against a vessel pressure of 0.276 MPa (40 psig).

The first manganese aerosol-generation test (LACE-DT-6) was conducted in a 0.13-m^3 development test vessel using an argon atmosphere under a gage pressure of 0.276 MPa. A second manganese aerosol-generation test (LACE-DT-7) was conducted in the AMIT test vessel containing a 50/50 vol % N_2 and steam mixture at 280°C and 0.276 MPa (40 psig). This test environment simulated the environment expected in the aerosol mixing vessel to be used in the first LACE test.

The next test of the LACE series was a reliability test (LACE-DT-8) conducted in the NSPP vessel (38.3 m^3) to demonstrate operation of the plasma torch for an extended period (60 min) against a vessel pressure of 0.276-MPa gage (40 psig). This test was conducted with no aerosol generation and there were no apparent problems resulting from this extended operation.

The last test of the LACE series was a Mn_2O_3 aerosol behavior test in the NSPP vessel in a condensing steam-air environment.

The LACE test series demonstrated that the plasma torch method is feasible for manganese aerosol generation under LACE test conditions; suitable aerosol generation rates remain to be demonstrated on-site using the actual LACE plasma torch aerosol generation system.

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